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DEVELOPMENTS IN THE HARMONIC ANALYSIS METHOD FOR THE NONDESTRUCTIVE DETERMINATION OF CASE DEPTH OF CARBURIZED STEEL

Technical Report

H. P. Hatch
K. A. Fowler

Date 20 May 1966

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DEVELOPMENTS IN THE HARMONIC ANALYSIS METHOD FOR THE NONDESTRUCTIVE DETERMINATION OF CASE DEPTH OF CARBURIZED STEEL

Technical Report

H. P. Hatch
K. A. Fowler

DA PROJECT TITLE: Magnetic and Mechanical Hardness Tests for Determining Case and Core Properties of Carburized Steel Parts

DA PROJECT: AW-5-15221

REPORT
SA-TR19-1520

ABSTRACT

The investigation concerned with the nondestructive determination of case depth of carburized steel by the harmonic analysis method was continued. The test method and instrumentation used in this investigation were described in detail in a previous Springfield Armory technical report, SA-TR19-1514. The harmonic analysis instrument developed previously in the program was utilized to study the effect of sample dimensions, chemical analysis, and the feasibility of employing a probe-type test coil. Results of this investigation demonstrated that the method was effective for measuring deep cases through .075 inch and shallow cases on samples having small cross-sectional areas. The effect of the demagnetizing factor was found to influence only the sensitivity of results, and substantial variations in alloying elements produced only minor differences in harmonic measurements. Correlation between case depth and harmonic phase shift was similar on samples heat-treated by either the gas or liquid-carburizing process. The ability to use a probe-type test coil for measuring case depth by this method was demonstrated by a prototype design.

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REPORT
SA-TR19-1520

SUBJECT

Nondestructive Electromagnetic Testing od Carburized Steel

OBJECTIVES

The investigation of the harmonic analysis method of measuring carburized case depth was extended to include a determination of the limiting range of depth which can be accurately measured, to establish the influence of the demagnetizing factor on harmonic measurements, and to develop a probe-type test coil so that the evaluation of large or selectively hardened components would be permitted.

CONCLUSIONS

1. At a fundamental frequency of 100 Hz, the harmonic analysis method is effective for the measurement of deep case depths up to at least .075 inch.

2. Harmonic analysis results are similar on samples heat-treated by either the liquid or gas-carburizing process.

3. Seventh harmonic measurements are applicable to the evaluation of shallow cases on samples having small cross-sectional areas.

4. Substantial variations in alloying elements in three different grades of carburizing steels produced only minor differences in harmonic measurements.

5. The effect of the demagnetizing factor (length-to-diameter ratio) on harmonic measurements was found to influence only the sensitivity of results.

6. A prototype design established the feasibility of using a probe-type test coil for measuring case depth by the harmonic analysis method.

RECOMMENDATIONS

On the basis of the results of this and earlier investigations, the following recommendations are made:

1. Continue a program of testing a number of production components and correlate nondestructive test results with case depths determined metallographically.

2. Determine if the significant variations in permeability, caused by differences in tempering temperature and core microstructure, can be distinguished nondestructively by electromagnetic methods.

3. Develop the probe-type measuring device shown to be feasible in this investigation. Emphasis should be on miniaturization and optimum configuration of probe core.

1. INTRODUCTION

This work represents an extension and continuation of investigations conducted in FY 64-65 which were previously reported.[1],[2],[3]* In earlier investigations, several electromagnetic methods were considered and evaluated as a means of nondestructively measuring the case depth of carburized steel parts, and one method, the harmonic analysis method, was found to be generally applicable. Results showed that harmonic phase shift not only correlated well with case depth, but could be made relatively insensitive to selected interfering variables intentionally introduced in a number of experimentally heat-treated samples.

The basic test principle involves the measurement of variations in the nonlinearity of magnetic response in terms of the distortion generated when a ferromagnetic material is under the influence of a sinusoidal-exciting field. The distortion is in the form of odd-order harmonics which can be filtered from the voltage wave developed in the secondary winding of a test coil. After the individual harmonic components have been extracted from the distorted secondary voltage wave form, the harmonic amplitude and phase, as well as the harmonic in-phase and quadrature components, are measured.

Previous work has established that the results of harmonic analysis measurement of case depth are primarily influenced by variations in the surface carbon content. However, the selection of the harmonic voltage parameter best suited for correlation with case depth may be dictated by the nature of other process variables that are present. In this respect, the value of being able to directly measure the in-phase and quadrature components of a selected harmonic frequency has been demonstrated by effectively separating two simultaneously changing variables, i.e., case depth and tempering temperature.[3]

Because of the significant results obtained by use of the harmonic analysis method, work has proceeded to determine the limitations in evaluating both light and deep cases produced by various carburizing treatments. In addition, investigations have been conducted to determine the feasibility of utilizing a probe-type test coil in place of the encircling solenoid to permit evaluation of large or selectively

*Superior numbers, in parentheses, appearing in this report refer to sources listed in the APPENDIX as LITERATURE CITED.

1. INTRODUCTION - Continued

hardened components. The instrumentation and test circuit of the prototype harmonic analysis instrument used in this investigation as well as the test principles involved are fully described in Springfield Armory Technical Report, SA-TR19-1514, and will not be repeated here. However, a block diagram of the test instrument is shown in Figure 1 to illustrate how measurements of the various harmonic-voltage components were obtained.

2. RESULTS AND DISCUSSION

a. Effect of Sample Dimensions

The work completed in FY 65 demonstrated the relationship between third and fifth harmonic voltage parameters and variations in case depth of carburized steel. The investigation, however, was primarily concerned with samples of a representative size and cross-section in the form of three-inch long tubes, 3/4-inch outside diameter with 1/4-inch wall thickness which were heat-treated only by the liquid-carburizing process. As part of the present investigation, it was decided to initiate a program of testing a limited number of production components heat-treated by various carburizing methods and having different dimensions from those of the previous test samples. As a result, a number of gas-carburized components, containing variations in case depth, were obtained from two industrial firms. These firms had expressed a willingness to supply samples representative of typical components for the exchange of information concerning the non-destructive measurement of case depth by the harmonic analysis method. Typical samples included light cases in the range of .004 to .012 inch as well as substantially heavier cases up to .080 inch.

One group of 80 gas-carburized production components, consisting of five different heat-treat lots, were in the form of short, thin-walled tubes 3/4 inch long, one-inch outside diameter, and .026-inch wall thickness. Preliminary third and fifth harmonic phase and amplitude measurements taken on a few selected components produced results which were inconsistent with those experienced on the previous carburized test samples. The first parameter to be considered as a reason for this discrepancy was the relatively large demagnetizing factor (small length-to-diameter ratio) of the component and its effect on harmonic measurements. To resolve this question, two sets of test samples were prepared from 1020 steel in the form of one-inch O.D. tubes with various lengths of 3/4 inch, 1-1/4 inches, two inches, and three inches. One set had a wall thickness

2. RESULTS AND DISCUSSION - Continued

of .035 inch and the other .075 inch. The samples were carburized for different lengths of time to produce variations in case depth for each length and wall thickness; then, all samples were subjected to extensive measurements which included the third, fifth, and seventh harmonic-voltage components.

Results of this investigation provided the information necessary for determination of the measuring parameters required to evaluate the thin-walled production components. Figure 2 is a plot of both third and fifth harmonic phase angle versus case depth for samples having .075-inch wall thickness and various lengths, and illustrates that an increase in the demagnetizing factor only decreases the sensitivity of results. The curves shown in Figure 2 are similar to those obtained in a previous investigation[3] using the three-inch long test samples with .250-inch wall thickness. Figure 3, however, which illustrates the results of measurements on the samples having .035-inch wall thickness, indicates that wall thickness, or the cross-sectional area, of the tube is the factor which is predominantly responsible for the difference in response of harmonic measurements to variations in case depth. Figures 2 and 3 show that third and fifth harmonic measurements provide good correlation with case depth for samples with .075-inch and larger wall thickness, whereas it was necessary to go to the seventh harmonic in order to obtain an unambiguous correlation with case depth on samples having .035-inch wall thickness.

Therefore, seventh harmonic phase and amplitude measurements were made on all of the .026-inch wall thickness production components. The components were carburized in an atmosphere having a 1.1 per cent carbon potential. Table I shows the carburizing time for each of the five different lots.

2. RESULTS AND DISCUSSION - Continued

TABLE I

Heat-Treat Lot	Carburizing Time
A	Copper Plated - 40 min.
B_1	10 min.
C_1	20 min.
A_1	40 min.
D_1	60 min.

Figure 4 is a plot of the seventh harmonic phase angle versus indicated carburizing times. The vertical line at each carburizing time represents the spread of readings for each lot since several components in each lot produced the same reading. To confirm this curve, two to three components from each lot were destroyed for metallographic examination. Results of this examination are shown in Table II.

TABLE II

Sample	Lot	ϕ_7	Total Case Depth
6	B_1	183°	5.5×10^{-3} inches
7	B_1	180.5°	5.6 " "
3	B_1	181°	5.8 " "
4	C_1	192°	7.2 " "
6	C_1	195°	7.4 " "
2	A_1	211°	10.0 " "
11	A_1	208.5°	10.2 " "
4	A_1	211°	10.0 " "
5	D_1	218.5°	12.3 " "
6	D_1	220.5°	12.5 " "

2. RESULTS AND DISCUSSION - Continued

Figure 5 is a plot of the data recorded in Table II showing excellent correlation between seventh harmonic phase shift and case depth of a gas-carburized production component. The results obtained using this component, which has a large demagnetizing factor and a small cross-sectional area, have helped to demonstrate the versatility of the harmonic analysis method. This method provides a relatively large number of measuring parameters sometimes required to establish an unambiguous relationship between the test results and the desired material variable - in this instance, case depth.

b. Effect of Chemical Analysis

To determine the effect of variations in chemical composition on harmonic measurements for the evaluation of case depth, heat-treated samples, which were obtained from another industrial firm, were fabricated from three different grades of carburizing steels. The alloys selected were AISI 4620, 8617, and 9310. Table III shows the accepted range of the major alloying elements.

TABLE III

AISI	C	Mn	Ni	Cr	Mo
8617	.15-.20	.70-.90	.40-.70	.40-.60	.15-.25
4620	.17-.22	.45-.65	1.65-2.0	--	.20-.30
9310	.08-.13	.45-.65	3.0-3.5	1.0-1.4	.08-.15

Previous investigations included only 8620 steel with case depths ranging from 0 to .025 inch[3],[4] since this is the material and maximum case depth often used in the fabrication of critical, high-performance weapon components at the Springfield Armory. Therefore, it was decided to extend this part of the program to include a greater range of case depths in order to determine the limitations of the harmonic analysis method in evaluating deep cases produced by carburizing. The samples were in the form of cylinders, 5/8 inch in diameter and 2-1/2 inches long. They were gas carburized in production furnaces at a carbon potential of 1.10 per cent for various lengths of time to produce case depths in the range of 0 to .080 inch, then quenched in oil at room temperature. After heat-treatment, a 3/4 inch section was cut from the end of each sample for the metallographic determination of case depth.

2. RESULTS AND DISCUSSION - Continued

Harmonic measurements were taken at a fundamental frequency of 100 Hz on all samples of the three different alloys, using the harmonic analysis instrument and test procedures described in a previous technical report.(3) Figure 6 is a plot of the results of these measurements and illustrates the correlation obtained between third harmonic phase shift and case depth up through .075 inches for each of the three carburizing steels. Considering the relatively large differences in both the nickel and chromium-alloying elements, the substantial amounts of austenite retained in the deep-cased 9310 samples, and the fact that all previous work was limited to case depths up to .025 inch, the results illustrated in Figure 6 are most promising. The curves for each of the steels are not only similar, but fall within a relatively narrow scatterband. In addition, the slope of the curves from 0 to .025 inch is identical to that previously obtained using liquid-carburized 8620 test samples.(3)

c. Development of Probe-Type Test Coil

Up to this time, only a solenoid test coil has been used in the investigation of the harmonic analysis method where the test sample or component is inserted into the encircling field coil for measurement. A test coil of this configuration has, of course, size limitations and it was, therefore, decided to investigate the feasibility of employing a probe-type test coil rather than an encircling coil to permit evaluation of large or selectively hardened components.

Because of the requirement that the applied field wave form be sinusoidal with as little harmonic content as possible(3), it was considered desirable to utilize an air-core probe where the sample to be tested is the only ferromagnetic material present in the magnetic circuit. Several probe configurations were investigated, but all were found to be impractical because of the large demagnetizing factor encountered when applying an electromagnetic field perpendicular to the surface of a test piece. For this reason, sufficient field strength to generate harmonics could not be obtained by this approach without supplying excessive current to the field coil, which caused severe overheating of the winding. Therefore, emphasis was placed on the use of a ferromagnetic core in order to produce a higher level of field strength required for measurements. Probe coils were designed containing various ferromagnetic materials in various shapes. The most promising configuration investigated was an elongated "U" core fabricated from silicon iron transformer laminations. A photograph of the prototype design is shown in Figure 7. The core is 2-1/2 inches long and each leg is 3/8 inch wide. It consists of a stack of 10 laminations, each lamination being .014 inch thick. The primary, or field, winding is one inch long and contains 450 turns of AWG No. 32HF wire. The secondary winding, or search coil, is 1/8 inch long and contains 120 turns of AWG No. 36HF wire. Sufficient field strength for the

2. RESULTS AND DISCUSSION - Continued

generation of harmonics was obtained with this configuration, but harmonic distortion resulting from the core material was added to that of the test specimen. Subsequent testing, however, demonstrated that the added distortion had only a minor effect on the results.

As a basis for evaluation of the effectiveness of probe-coil measurements, extensive harmonic measurements were taken in an encircling solenoid on a set of samples containing variations in case depth and variations in length-to-diameter ratio. A comparison was then made with the results obtained using the probe coil on the same set of samples. Figure 8 is a plot of the results and illustrates that the probe-coil measurements exhibit the same relationship between case depth and third harmonic phase shift as the solenoid measurements. In addition, the probe-coil measurements were not affected by variations in the demagnetizing factor as were the measurements obtained in the solenoid.

The positioning of the probe coil on the test sample was not found to be critical when a nonconducting gap of .003-.005 inch was introduced between the core-pole faces and the test piece, and measurements were easily reproduced. Therefore, from these results, the feasibility of using a probe-type test coil to measure variations in case depth by the harmonic analysis method has been established.

3. SUMMARY

The harmonic analysis method has been shown to be an effective means of nondestructively evaluating the case depth of carburized steel. In earlier work, it was found that harmonic phase shift not only correlated well with case depth, but could be made relatively insensitive to selected interfering variables intentionally introduced in a number of experimentally heat-treated test samples. It was also demonstrated by comparative measurements made on hardened and tempered plain carbon steels that the results of harmonic analysis measurements of case depth are primarily influenced by variations in the surface carbon content. In continuing the program with the prototype harmonic analysis instrument, this investigation has demonstrated that the method is effective for the measurement of deep cases through .075 inch, and that results are similar on samples heat-treated by either the liquid or gas-carburizing process. Seventh harmonic measurements were found to be applicable for the evaluation of shallow cases on samples having small cross-sectional areas, and experiments established that the effect of the demagnetizing factor influenced only the sensitivity of results. It was also found that

3. SUMMARY - Continued

substantial variations in alloying elements produced only minor differences in harmonic measurements. In addition, a prototype design established the feasibility of using a probe-type test coil for measuring case depth by the harmonic analysis method. These results, therefore, demonstrate the advantage of the method where a relatively large number of voltage parameters provide the versatility sometimes required for the establishment of an unambiguous relationship between test results and the desired material variable.

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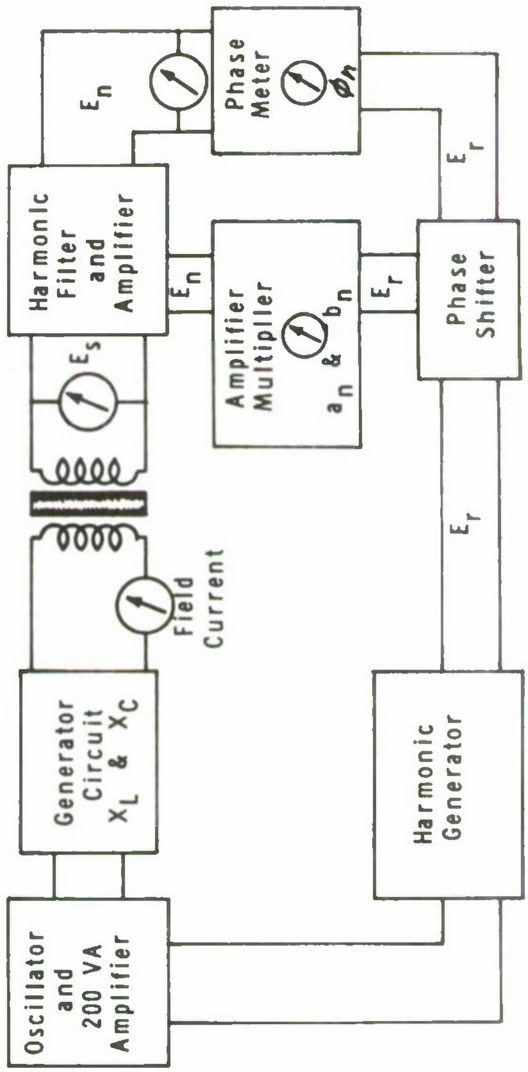

FIGURE 1. Block Diagram of Harmonic Analysis Instrument.

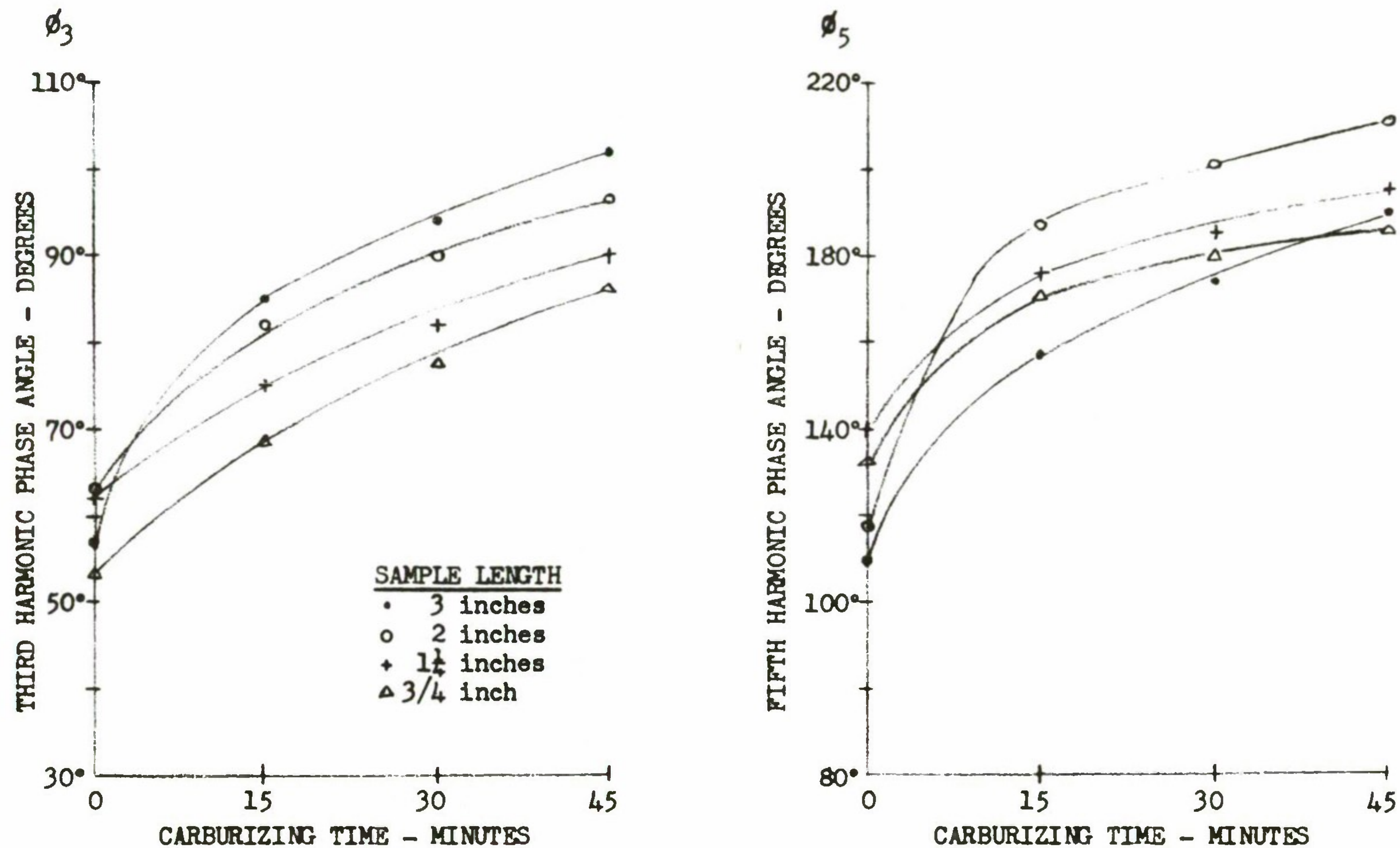

FIGURE 2. Effect of Demagnetizing Factor on the Relationship Between Harmonic Phase Shift and Case Depth. Samples .075-inch Wall Thickness, 1 inch O.D. Fundamental Frequency - 100 Hz.

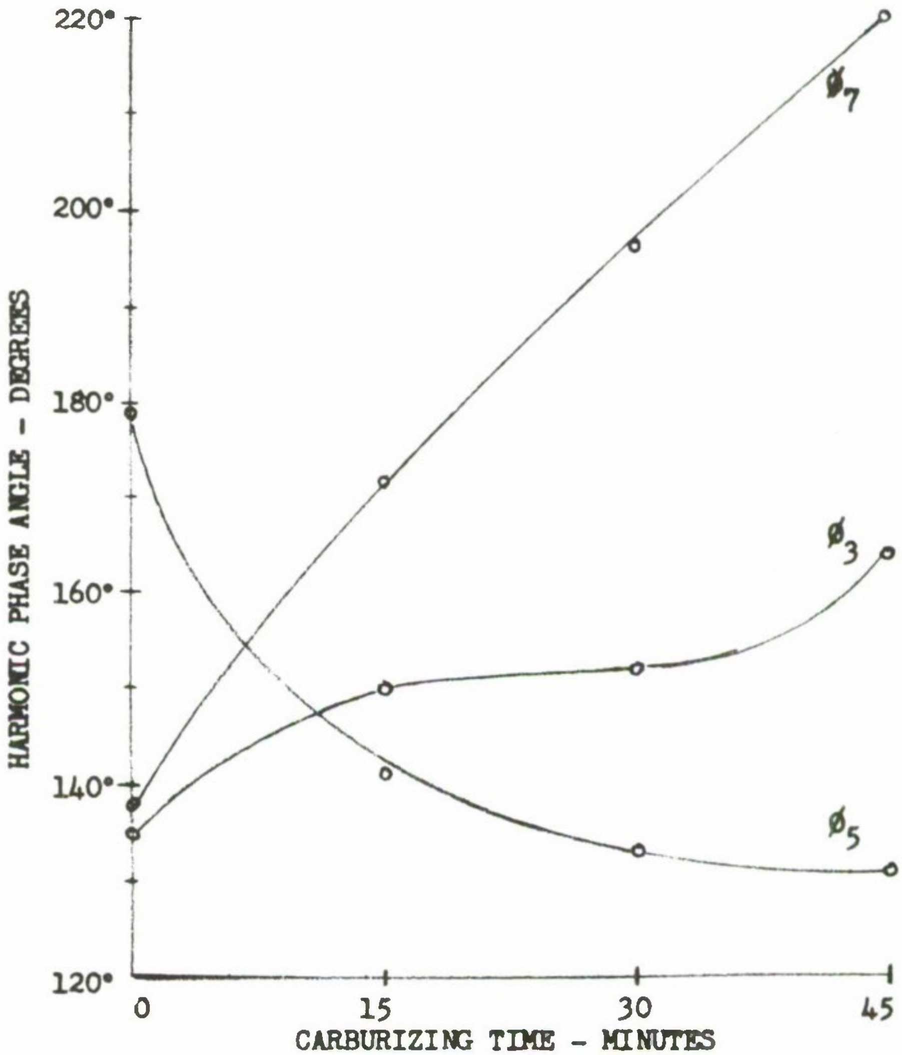

FIGURE 3. Comparison of Correlation Between Third, Fifth, and Seventh Harmonic Phase Shift and Carburizing Time of Thin-Walled Tube, 1 inch O.D., 3/4 inch Long, and .035-inch Wall Thickness. Fundamental Frequency - 100 Hz.

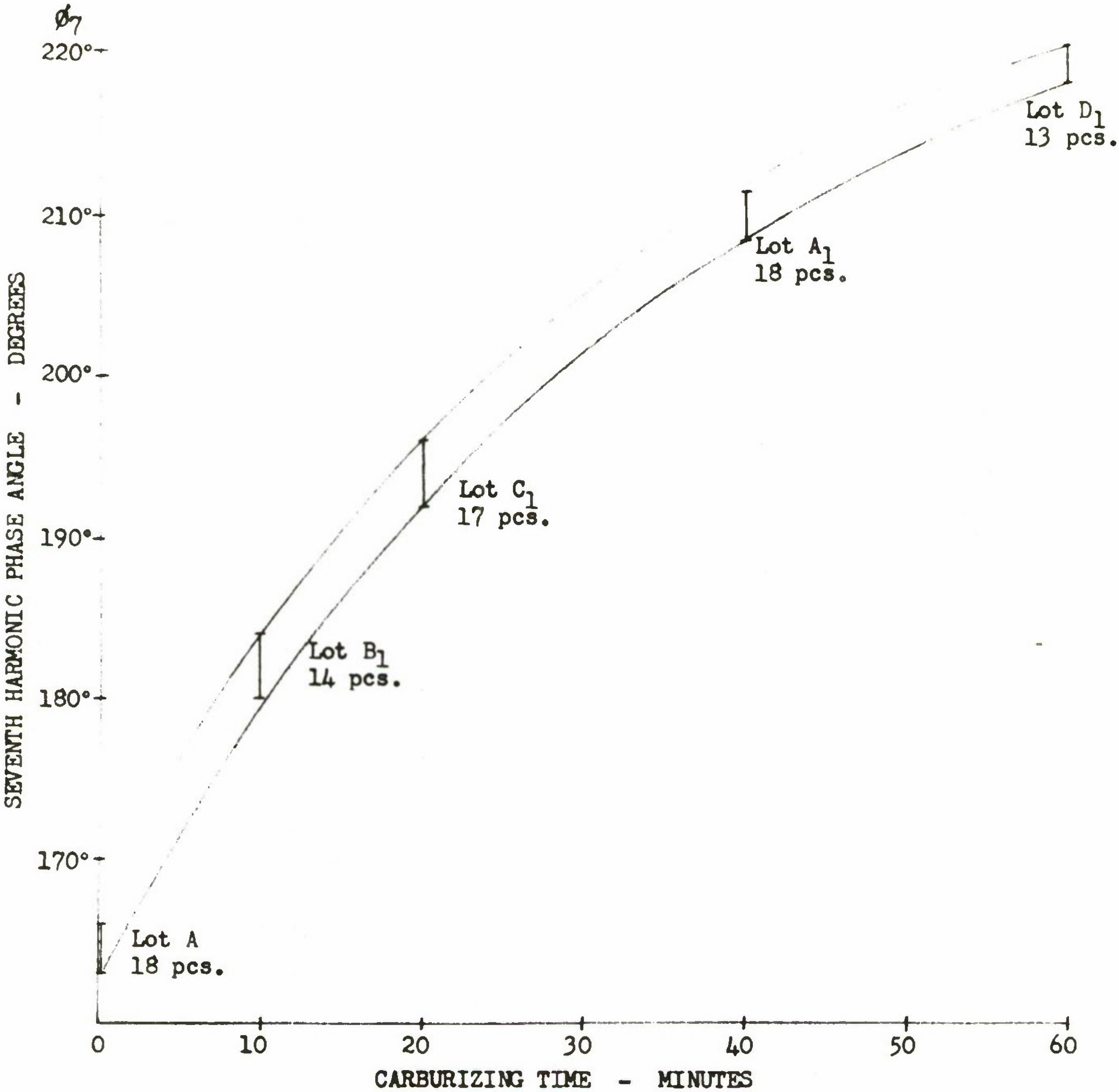

FIGURE 4. Plot of Seventh Harmonic Phase Angle Versus Carburizing Time on .026-inch Wall Thickness Production Components. Fundamental Frequency - 100 Hz.

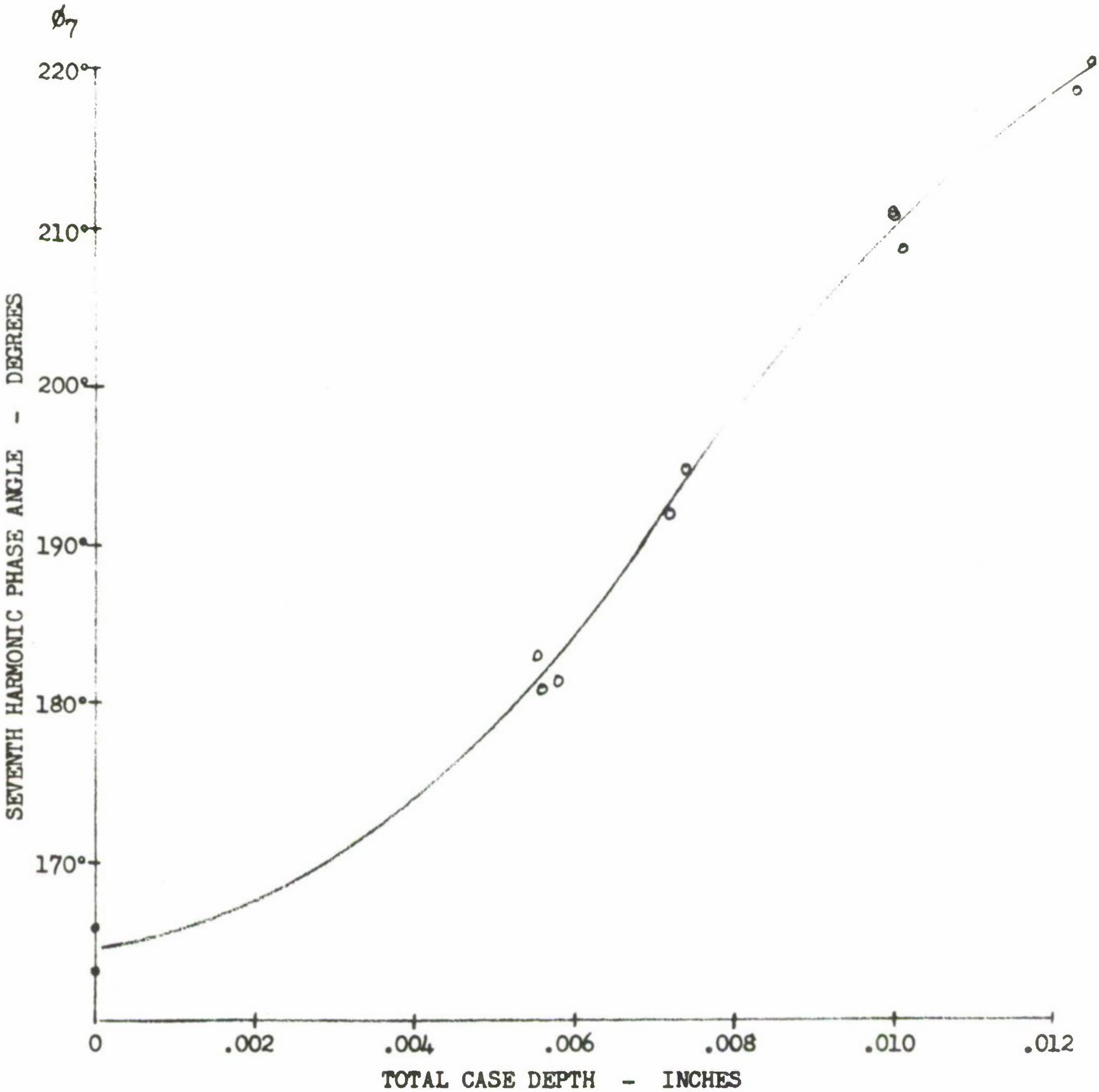

FIGURE 5. Plot of Seventh Harmonic Phase Angle Versus Case Depth on .026-inch Wall Thickness Production Components. Fundamental Frequency - 100 Hz.

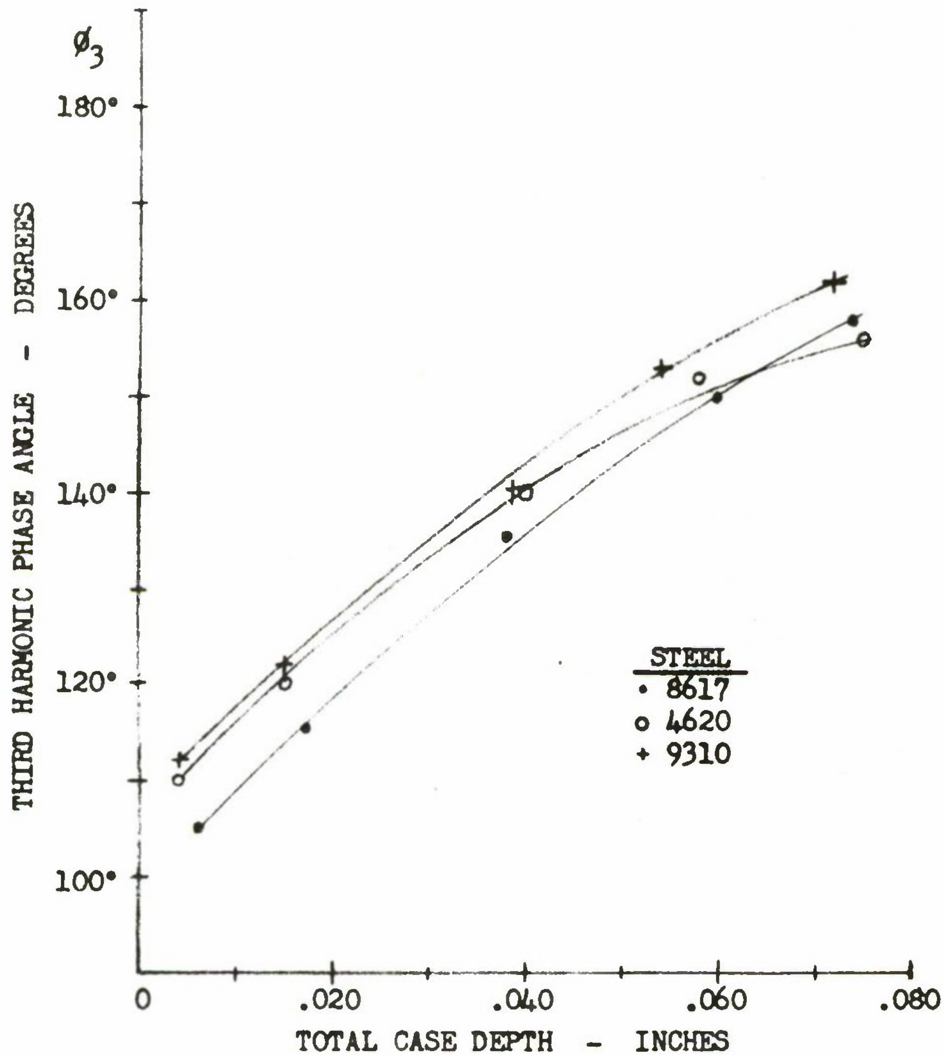

FIGURE 6. Plot of Third Harmonic Phase Angle Versus Case Depth Showing the Effect of Differences in Alloying Elements. Samples Were Gas Carburized and Oil Quenched. Fundamental Frequency - 100 Hz.

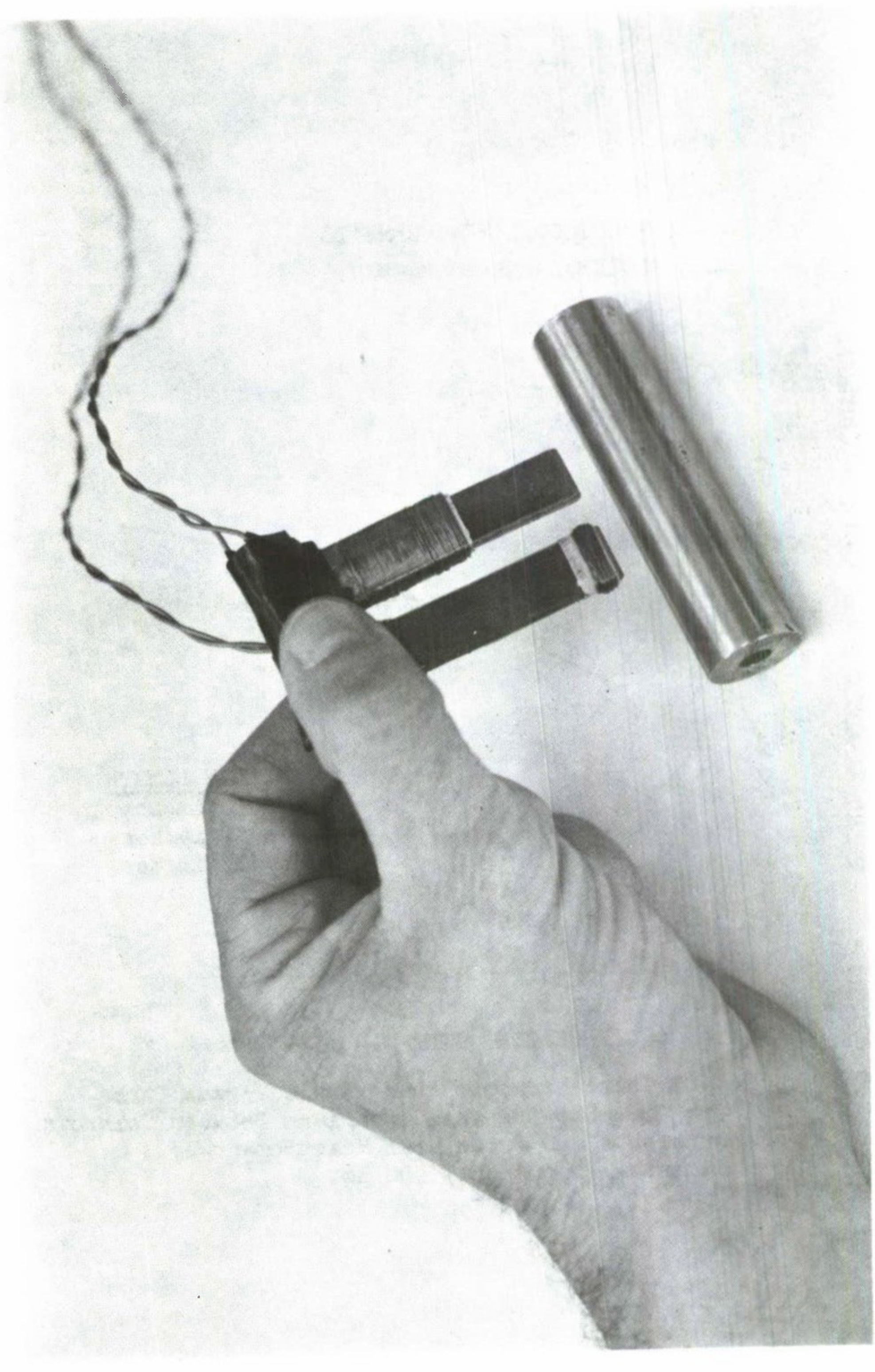

FIGURE 7. Photograph of Prototype Design of Probe-type Test Coil

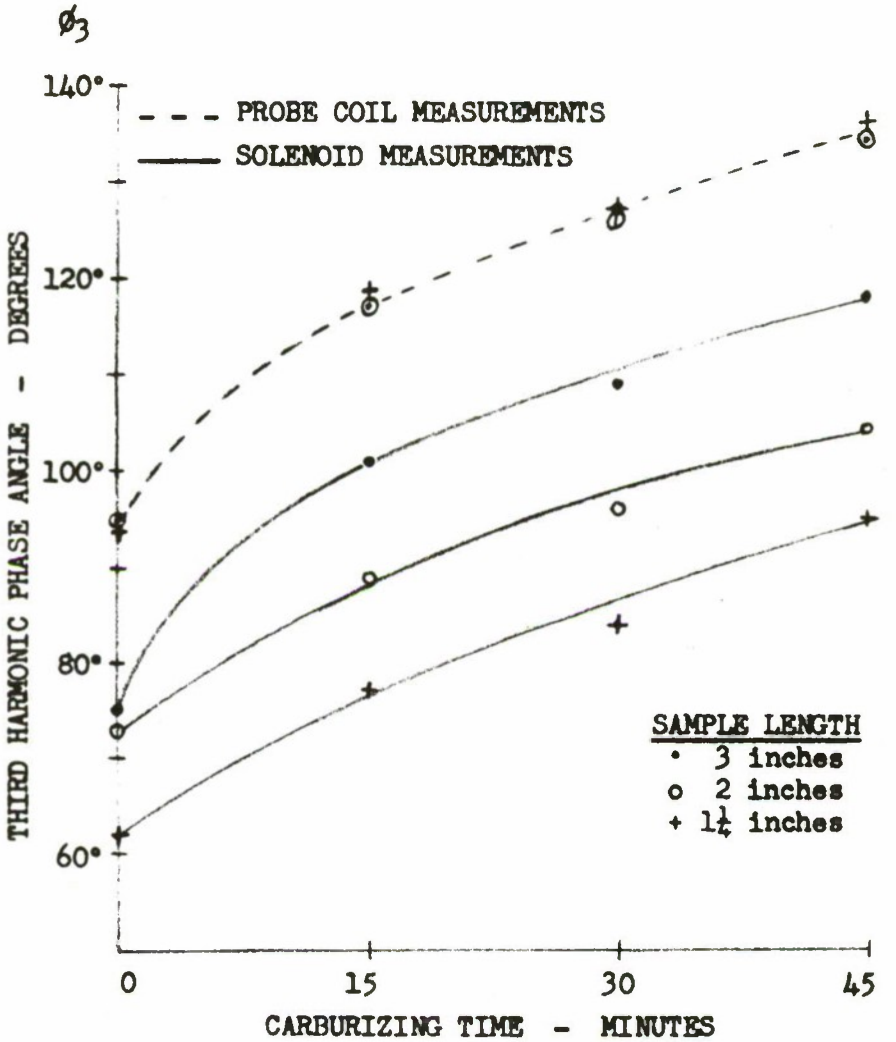

FIGURE 8. Plot of Third Harmonic Phase Angle Versus Carburizing Time Showing the Comparison Between Solenoid Measurements and Probe Coil Measurements. Fundamental Frequency - 100 Hz.

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13. ABSTRACT

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ABSTRACT

AD ________________ Accession ________________

Springfield Armory, Springfield, Massachusetts 01101
DEVELOPMENTS IN THE HARMONIC ANALYSIS METHOD FOR THE NONDESTRUCTIVE DETERMINATION OF CASE DEPTH OF CARBURIZED STEEL, H. P. Hatch and K. A. Fowler, Technical Report SA-TR19-1520, 20 May 1966, 26 pages including illustrations.

AMCMS CODE 4930.1, PROJECT AW-5-15221.
UNLIMITED DISTRIBUTION. UNCLASSIFIED REPORT.

The investigation concerned with the nondestructive determination of case depth of carburized steel by the harmonic analysis method was continued. The test method and instrumentation used in this investigation were described in detail in a previous Springfield Armory Technical Report, SA-TR19-1514. The harmonic analysis instrument developed previously in the program was utilized to study the effect of sample dimensions, chemical analysis, and the feasibility of employing a probe-type test coil. Results of this investigation demonstrated that the method was effective for measuring deep cases through .075 inch and shallow cases on samples having small cross-sectional areas. The effect of the demagnetizing factor was found to influence only the sensitivity of results, and substantial variations in alloying elements produced only minor differences in harmonic measurements. Correlation between case depth and harmonic phase shift was similar on samples heat-treated by either the gas or liquid-carburizing process. The ability to use a probe-type test coil for measuring case depth by this method was demonstrated by a prototype design.

1. Nondestructive testing
2. Electromagnetics
3. Harmonic analysis
4. Carburized steel